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HYDROLOGIC PARAMETERS RELATED to SITE CHARACTERISTICS for FOREST ROADS

by
Charles L. Kessler

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A Study Plan

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INTRODUCTION

There is a growing public concern that forest management operations, particularly road construction, be conducted economically and with minimum impact to the water resource. Forest roads expose large amounts of bare soil and therefore may tremendously increase the potential for surface erosion. The amount of erosion from such sites depends greatly upon the geologic parent material of the area and the characteristics of the soil derived from this material. Hydrologists, foresters, watershed managers and forest engineers need accurate estimates of on-site sediment yield from forest roads in order to be able to estimate the impact of land management activities on both on-site and off-site water quality. These sediment yield estimates may also be used to design and implement cost-effective erosion control techniques.

Generally, land managers have based their sediment yield predictions on the Universal Soil Loss Equation (USLE) and empirical relationships between site characteristics and runoff and sediment yield. The USLE is based on research conducted on agricultural areas and therefore has to be adapted for use in the forest environment. The empirical relationships are usually derived for an entire watershed area and must be modified in some manner to make estimates for smaller areas. There is a need for process-based technology to predict runoff and sediment yield from forest roads in order to more accurately plan land management activities that produce a minimum environmental effect.

The USDA-Water Erosion Prediction Project (WEPP) is a cooperative effort designed to develop new generation water erosion prediction technology for use by organizations involved in soil and water conservation and environmental planning and assessment (Foster 1986). The goal of the project is to improve the erosion prediction technology based on modern hydrologic and erosion science to such a point that WEPP will provide a significant improvement over USLE and

when given the choice of models, a user will choose WEPP. The development of personal computers now makes it possible to solve complex mathematical algorithms quickly and easily in the field and office, and WEPP is designed to convert available knowledge to a form that the user can easily apply. The Engineering Technology Research Work Unit of the U.S. Forest Service Intermountain Research Station is responsible for conducting all the research on forest roads for inclusion in the WEPP model.

The important first step of any attempt to predict surface erosion is the estimation of the amount and timing of runoff that may result from a precipitation event. The Agricultural Research Service (ARS) in Tucson, Arizona, has developed a program called IRS to compute infiltration and rainfall excess on a plane and then to route the runoff on the plane to produce an overland flow hydrograph that can be used in the WEPP model (Stone et al. 1987). This program determines the rainfall excess using the Green-Ampt equation and routes the excess using the kinematic wave equation. Input requirements for running the IRS program include parameter values for the Green-Ampt infiltration equation.

Much of the previous work concerning infiltration has been restricted to agricultural and rangeland soils. The WEPP Model is no exception. It primarily relates Green-Ampt parameters to agricultural soil characteristics. Little work has been conducted on forest roads. These sites present a unique set of problems because they may be constructed in the C horizon or parent material and have high bulk density. In the Intermountain West, the majority of sediment produced on forest land is from forest roads (Megahan et al. 1981) and so relating Green-Ampt parameter values to such sites is a necessary effort.

The project covered in this study plan will examine the infiltration process on four types of soil/geologic material commonly found in the Northern

Rocky Mountains; volcanic, granitic, Belt quartzite, and soft sediment. A programmable rainfall simulator will be used to apply rainfall to forest roads built in these materials. The results of the study will be used to develop values for the infiltration parameters used in the WEPP model. It is believed that the use of rainfall simulation will allow for the derivation of parameter values that can enhance the model's capability for predicting surface erosion from forest roads.

The objectives of this study are:

1. Apply simulated rainfall in two intensities to selected forest road traveledways and measure the resulting runoff;
2. Derive values for the hydraulic conductivity and the capillary suction head across the wetting front for each type of soil/geologic material so that these values may be used in the WEPP model;
3. Relate these values to site soil properties for each type of soil/geologic material, and
4. Use these relationships to estimate Green-Ampt parameters using soil/geologic material properties.

BACKGROUND

Rainfall Simulation

Attempts to simulate natural rainfall by means of a sprinkling infiltrometer began in the early 1930's (Peterson and Bubenzer 1986). The rainfall simulators (rainulators) developed since that time have played an important role in erosion and infiltration research. Much of the Universal Soil Loss Equation was developed with data that was collected during simulated rainfall. The major emphasis recently has been the development of rainulators that can closely simulate the characteristics of natural rainfall events. Defining the storm characteristics that are of importance is generally the first

step in selection or development of a rainfall simulator. Peterson and Bubenzer (1986) arrived at the following list of criteria after an extensive literature review.

1. The drop-size distribution should be similar to that of natural rainfall.
2. The drop velocity at impact should be near terminal velocity.
3. The rainfall intensity should correspond to natural conditions.
4. There should be uniform rainfall and random drop-size distribution.
5. The total energy of the simulated storm should approach that of natural rainfall.
6. The storm patterns of the simulated rainfall should be reproducible.

Impact velocity, drop-size distribution and intensity are the basic design parameters which must be considered in the design or selection of a rainfall simulator (Peterson and Bubenzer 1986). There has been a move toward using simulators with oscillating spray nozzles that point down at the surface to be rained upon because such a configuration has been found to meet the first two criteria. While the spray from these nozzles strikes the surface intermittently, the short period between spray applications appears to have only minimal effects on infiltration, runoff, and erosion (Foster et al. 1982). Two additional features of this type of design are that excess water that does not fall to the ground may be recirculated through the application system to reduce the amount of water needed and the continuous flow through the nozzles also tends to eliminate the problem of nozzle clogging with foreign material from the water source which had occurred in earlier simulators. The development of a programmable simulator (Foster et al. 1982) allows for varying storm intensity either during a single application period or between different application periods.

Infiltration

Runoff is the driving force for erosion and sediment transport so it is essential that the runoff hydrograph be accurately predicted. Given the rainfall rate and certain surface characteristics, infiltration capacity of the soil determines, for a given storm, the amount and timing of excess rainfall that is available for runoff and depression storage on the surface.

Infiltration refers to the process by which water moves from the surface of the soil into the pores of the soil profile. This process may occur when water is ponded on the surface and when water is applied to the surface at a constant rate (Fig. 1). The rate at which the water enters the soil surface is called the infiltration rate, f. In the ponded condition, at time zero, water is ponded at a shallow depth on the soil surface, and water is continually added at a rate which maintains a constant ponding depth. Under these conditions the infiltration rate is limited only by soil-related factors. The maximum rate at which water can enter the soil at a particular point under a given set of soil conditions is commonly referred to as the infiltration capacity of the soil. Infiltration capacity generally decreases with time due to the deterioration of soil structure and the detachment of particles that cause the blockage of pores, the swelling of clays upon wetting, the entrapment of air by the incoming water, and a decrease in the matric suction gradient as the soil surface approaches saturation (Hillel 1981). As the infiltration process continues for a sufficiently long period of time, the infiltration capacity will approach a constant rate, f_c, which is generally assumed to be equal to K_s, the saturated hydraulic conductivity at a residual air content.

When water is applied to the surface at a constant rate, R, the infiltration rate during the early portion of the application period will be equal to R if R is less than the infiltration capacity of the soil (Fig. 1).

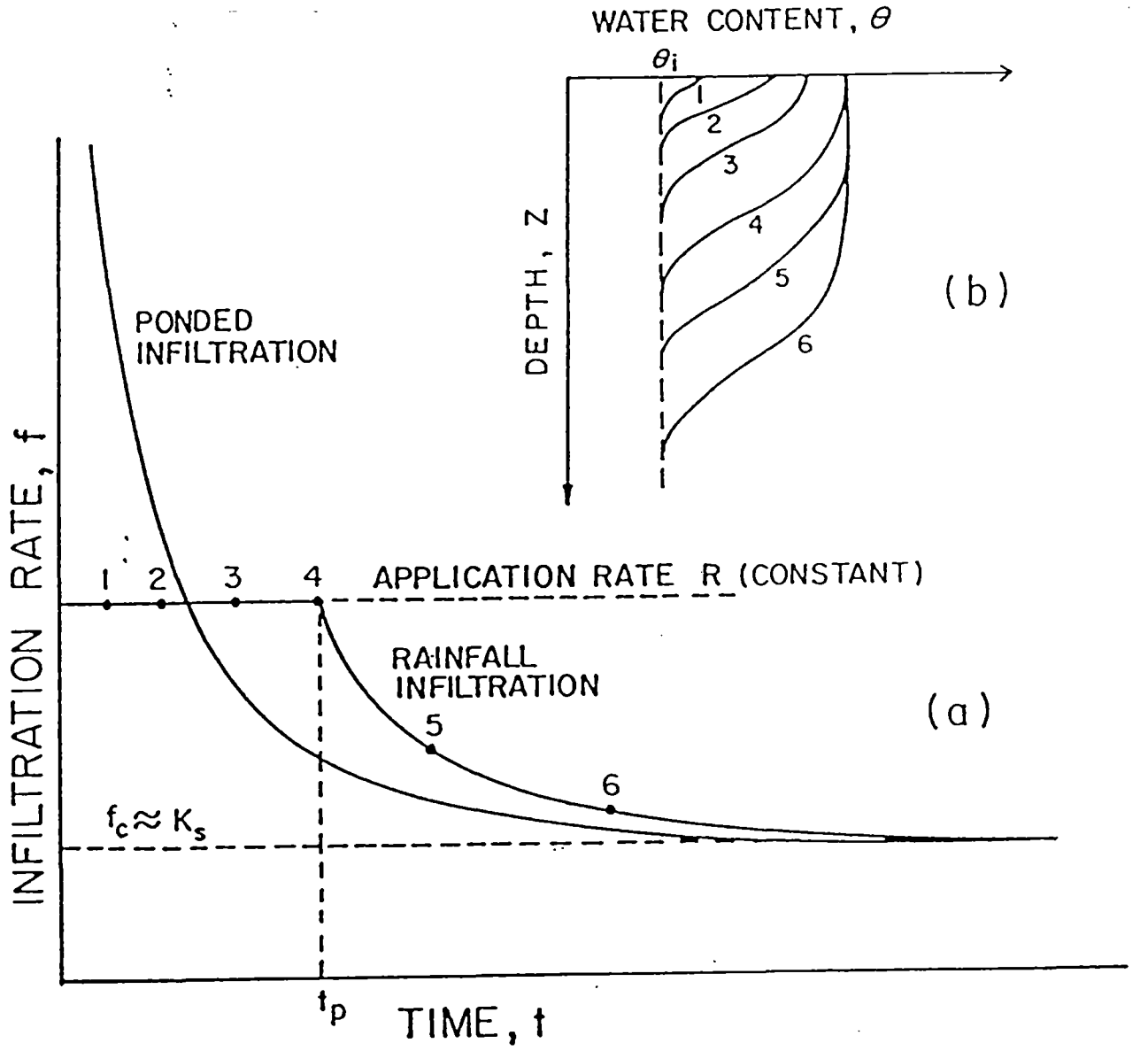

Fig. 1. (a) Infiltration rate versus time for a ponded surface and for a constant application rate, R. (b) Water content versus depths at times denoted by 1-6 in part (a) for the constant application rate. (Skaggs and Khaleel 1982).

This is a supply controlled situation and is shown in Figure 1 as points 1-3 on the rainfall infiltration curve. This situation will exist as long as R remains less than the infiltration capacity. As infiltration continues, the infiltration capacity will decrease until it becomes less than R and ponding will occur on the soil surface. Infiltration will now be controlled by the soil profile. Additional application of water at a rate in excess of the infiltration capacity will result in surface storage and runoff.

The infiltration capacity of a given soil is dependent upon several factors. The initial water content of the soil, θ_i, will affect the infiltration capacity due to the capillary suction - water content relationship. An initially wet soil would have a lower initial infiltration capacity due to a smaller suction gradient than that found in an initially dry soil. The wetter soil would reach a constant infiltration rate more quickly than the dryer soil. This constant rate is generally independent of θ_i since it is basically a gravity induced rate that is practically equal to K_s. Therefore, the higher the K_s of a particular soil, the higher the final infiltration capacity. Hydraulic conductivity is related to the total porosity, pore size distribution, and pore geometry of the soil and the properties of the fluid flowing through the soil.

Profile conditions also play a role in determining the infiltration capacity of a soil. A surface that is highly porous with an open structure has a greater infiltration capacity than a uniform soil. If a crust should form by the slaking action of raindrops on an unstable surface, the hydraulic conductivity of the surface will be decreased. Such a crust forms a hydraulic barrier which can reduce the initial and the final infiltration capacity. Layers of different texture or structure within the profile may affect the infiltration process due to the varying hydraulic conductivity of these layers. In a saturated condition, a clay layer in a coarser soil would impede flow due

to a lower K_s for the clay. In an unsaturated condition, a sand layer in a finer soil would retard the movement of water due to a lower hydraulic conductivity in the sand at equal matric suction.

The WEPP model calculates infiltration using a solution to the Green-Ampt equation for unsteady rainfall presented by Chu (1978). The original equation, developed in 1911, assumes that water enters the soil as slug flow resulting in a sharply defined wetting front which separates a wetted zone from a dry zone (Fig. 2). The hydraulic conductivity term of the original equation was expressed as "the linear rate at which water will sink through an area of soil, saturated and just covered with the water" (Green and Ampt 1911). The authors do note that total expulsion of the air from the interstices of the soil is extremely difficult even in this saturated condition. The infiltration rate equation used in the WEPP model is

$$f = K_s \left[1 + \frac{n\psi_f}{F}\right]$$

and its integrated form is

$$K_s t = F - n\psi_f \ln \left[1 + \frac{F}{n\psi_f}\right]$$

where:

f = infiltration rate (L/T),
K_s = saturated hydraulic conductivity (L/T),
n = available porosity (L/L),
ψ_f = capillary suction head across the wetting front (L),
F = cumulative infiltration (L), and
t = time.

The ψ_f term results from forces associated with the colloidal matrix such as adsorption, capillarity and curved air-water interfaces. The present WEPP model calculates a value for ψ_f using an exponential equation which incorporates clay content, sand content, and total porosity in the exponent.

The available porosity term is calculated as the effective porosity (n_e) minus the initial water content. The effective porosity is computed from the

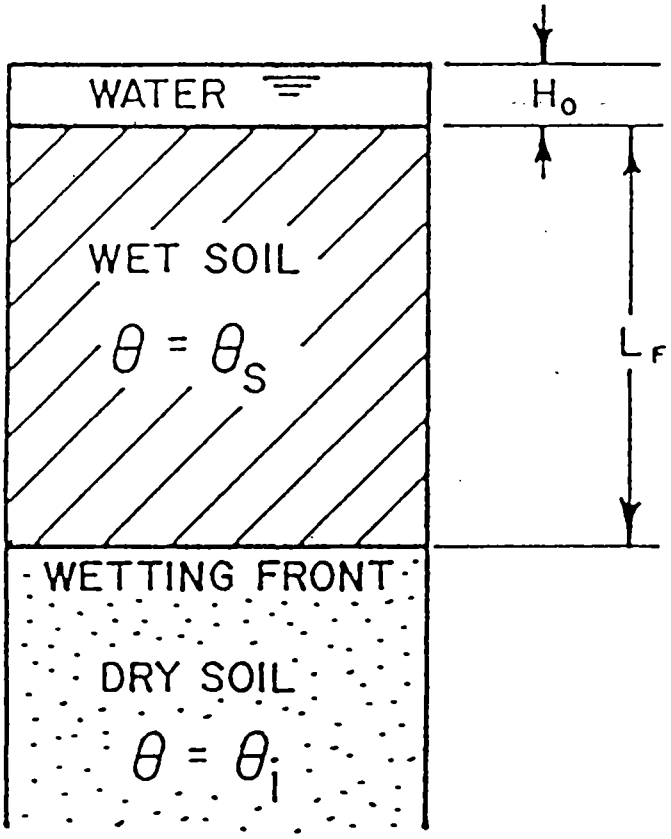

Fig. 2. The Green-Ampt model assumes slug flow with a sharp wetting front between the infiltrated zone and soil at the initial water content. The wet zone increases in length as infiltration progresses. (Skaggs and Khaleel 1982).

total porosity determined from the bulk density of the soil consisting of particles less than 2 mm in diameter which has been adjusted for entrapped air, residual water and coarse fragments (> 2 mm) (Rawls et al. 1987). The adjustment will be based upon relationships involving the bulk density of the fine earth soil (< 2 mm), clay content, sand content, the cation exchange capacity and the organic matter content of the soil.

The relationships utilized by the model have generally been developed for agricultural situations. Forest roads built in steep terrain may be constructed in C horizon material and often have significantly more coarse material than do agricultural soils. The entrapped air adjustment and the correction for coarse fragments used in calculating effective porosity in the WEPP model may not hold true for soils with greater than 50 percent coarse material by weight (Walter Rawls, personal communication). There is a definite need to examine the infiltration characteristics of forest road surfaces in order to develop relationships and values that may be used in the WEPP model.

Methodology

Site Selection

Preliminary site selection was conducted in October 1987 in the Deerlodge, Helena, Beaverhead, and Gallatin National Forests in Montana. One type of soil/geologic material was located on each forest. Volcanic material will be studied on the Deerlodge, granitic material on the Helena, Belt material on the Beaverhead, and soft sediment material on the Gallatin. Final site selection will be conducted during the 1988 field season and will be based upon: uniformity and extent of soil/geologic material; uniformity of plot gradient; width and length of the road traveledway; proximity to an adequate water source; and the ability to be able to close the roads to traffic for up to one month.

Soil scientists on each forest have aided in identifying representative areas for the establishment of research plots.

A selected section of road must have a running surface of native material (ungravelled). The section will be graded in order to create a condition that approximates a new construction condition as much as possible since the first year after construction is when a forest road produces the most sediment due to erosion (Megahan et al. 1981). Traveledway centerline slopes may vary between 4 and 10 percent and the section may either be insloped to a ditch or outsloped to a constructed fillslope.

Plot Establishment

Each plot will consist of 3 one meter square subplots in conjunction with a 1 m x 5 m subplot. Each subplot will be surrounded by metal boundaries. The boundary of each subplot will be oriented in such a way that the runoff from each plot will follow the true slope of the road (the path of flowing water across the road toward the ditch or toward the fillslope). The lower boundary of each subplot will serve as a collection gutter and will carry the runoff to a flow measuring device designed to accurately measures small flow volumes. The one meter square subplots will deliver runoff to two graduated cylinders that are connected to a manometer. The depth of water in the manometer will be recorded by an ISCO model 2870 flowmeter capable of measuring stage to 1mm. The 1 m x 5 m subplot will deliver runoff to a box flume equipped with the same type of flowmeter.

One of the 1 M^2 subplots will be selected to determine if surface sealing or crusting has a significant effect upon the infiltration process and the runoff hydrograph for the road traveledway. These subplots will be covered with 2 layers of window screen 2 cm apart and 10 cm above the soil surface while the other 1 M^2 subplots will be left uncovered. Repeated rainfall applications on

these subplots will show if the infiltration rate for the uncovered subplots is significantly lower than the infiltration rate for the covered subplot. If this is the case, the difference will be attributed to surface sealing. If surface sealing does occur, only the unscreened 1 M^2 subplots will be used in parameter estimation because they better represent the natural situation.

The 1 M^2 subplots are intended to provide detailed information on the infiltration process occurring on the road surface. Data from these subplots will be used in parameter estimation and to develop relationships between parameter values and site characteristics. The 1 M x 5 M subplot will integrate the spatial variability of road surface conditions and will provide information on how the entire running surface is responding to rainfall application. This subplot will be used to test the results of the analysis of the data from the 1 M^2 subplots.

One plot, consisting of the 4 subplots, will be established for each rainfall intensity to be used. Rainfall will be applied at two intensities, 1 inch per hour and 2 inches per hour, during a 30 minute application period. Ideally, there will be 2 replications of each intensity used in each type of soil/geological material. This may not always be possible due to scheduling constraints.

A network of recording and non-recording rain gauges will be established on each plot. Four tipping bucket intensity gauges will be located on the traveledway outside of any subplot boundary. Non-recording rain gauges will be located outside of the 1 M^2 subplots and at a one meter spacing around the outside of the 1 M x 5 M subplot. The gauges will be used to determine areal uniformity of rainfall and the mean rainfall over each subplot.

Rainfall Simulator

The rainfall simulator to be used is a modification of the Kentucky rainfall simulator (Moore et al. 1983) and the programmable simulator described by Foster et al. (1982). The simulator is equipped with 80150 Veejet spray nozzles because they appear to best simulate the natural rainfall characteristics of interest to this project (Meyer and Harmon 1979). Sprinklers will be contained in 6 M long modules with 4 sprinklers per module. The sprinklers will be 1.52 M apart within the module and will be driven from one end of the module by a shaft connected to an electric motor equipped with a clutch. The opposite end of the module will contain a reservoir that will be used to recirculate excess water within the system. The nozzles will oscillate back and forth parallel to the long axis of the module with the point of oscillation being the opening of the nozzle. Different application rates will be achieved by controlling the number of oscillations each nozzle makes which controls the time the nozzle is spraying onto the plot.

Four modules will be placed on a support frame above each plot. The modules will be positioned so that the line of the nozzles in adjacent modules are 4.33 feet apart. Adjacent modules will be staggered by 2.5 feet to provide for better plot coverage. The support frame will be situated so that the modules run perpendicular to the road centerline. The frame will be raised so that each nozzle is 10 feet above the road surface.

At least three rainfall applications of 30 minutes duration will be made on each plot. A dry run will be conducted at the existing soil moisture level. The plot will be allowed to recover for a period of time (generally overnight) and a wet run will be conducted. The plot may be covered with plastic between the dry and wet runs depending upon weather conditions. Immediately after all

the data has been collected from the wet run, a very wet run will be conducted. Additional runs may be conducted if deemed necessary for model development.

Field Data Collection

Gravimetric Soil Moisture Samples

Soil moisture samples will be taken prior to and immediately following each rainfall application. Samples will be obtained from randomly selected locations on the outside edge of each subplot. Samples will be taken at 0.1 foot increments to a depth of 0.3 feet. Rocks and large stones will be avoided during the sampling because they would tend to make the samples less accurate as a measure of actual soil moisture. This is in keeping with the WEPP assumption that coarse fragments do not hold a significant amount of water (Walter Rawls, personal communication).

Runoff Samples

ISCO model 2870 bubbler-type flowmeters will be installed on each box flume and in each manometer in order to record stage of flow through the flume and depth in each manometer. The flowmeter readings will be recorded by a data logger at 10 second intervals. Stage readings will be converted to flow in cfs based upon equations developed for each type of sampling device.

Soil Samples

Samples of the surface soil will be obtained prior to the first rainfall application. A portion of these large samples will be shipped to various WEPP laboratories for extensive characterization of the surface material from each sampling surface. The remainder will be sent to the project soil laboratory for particle size analyses.

Bulk density samples will be obtained from each subplot after the final rainfall applications. The cavity method (Walter Rawls - personal

communication) will be used to obtain bulk density samples for analysis in the project soils laboratory.

A qualitative description of the soil will be obtained at each site in order to aid with the SCS analysis of the large soil samples. The soil scientist on each National Forest will make a standard pedon description.

Data Analysis

The hydrologic parameters to be derived from the data collected in the field are the Green-Ampt parameters of hydraulic conductivity and capillary suction head. Different approaches exist for determining these parameters (Bouwer 1969, Ward 1986, Flerchenger and Watts 1987, Lane - personal communication) and this project will apply different methods of estimation to see which works best for forest roads.

Ward (1986) uses 2 graphical methods to determine saturated hydraulic conductivity (Kw) and capillary suction head (Hc). Ward uses different symbols, but his Kw corresponds to K_s and H_c is equivalent to ψ_f. The first method involves the use of a simple form of the Green-Ampt equation

$$f = a + \frac{b}{F}$$

where f is the instantaneous infiltration rate, F is the depth of accumulated infiltration and a and b are best fit parameters. Both f and F are plotted as functions of time based upon the runoff hydrograph from a rainfall application. The infiltration rate is measured as the rainfall rate minus the measured runoff rate. Flerchinger and Watts (1987) employed a lagging procedure to allow for travel time over large plots (1300 ft.^{2}), but that does not appear to be necessary when using smaller plots. A plot of f (Y axis) versus 1/F (X axis) is made using the data derived from the plots of f and F. This plot should provide a nearly straight line when some of the initial and final data points are

excluded to eliminate the effects of simulator operation. Assuming that as F gets large, f approaches the hydraulic conductivity, the Y-intercept (a) then represents Kw, and the slope of the straight line is b.

The capillary suction head can be calculated by

$$Hc = \frac{b}{(a)(ds)(n)}$$

where ds is the difference between initial soil saturation and final soil saturation (equal to 1) in the transmission zone and n is the porosity. The ds term may be calculated by ds

$$ds = 1 - Si$$

where Si is initial soil saturation and is equal to

$$\frac{AMC\ (1-n)2.65}{n}$$

where AMC is the antecedent moisture content.

At times, rainfall simulation data does not produce values of F that are relatively large and so it is possible to obtain negative values of a. Kw and Hc are then negative values that have no physical interpretation. Ward (1986) proposes a second graphical approach. This approach includes the plotting and examination of data for f and F found in the first approach. The steady runoff rates for the last 10 to 15 minutes of the application period are used to calculate an average infiltration rate which is assumed to be equal to Kw, the saturated hydraulic conductivity. The equation

$$\frac{f-Kw}{Kw} = \frac{C}{F}$$

where C is the slope of a no intercept line (passing through the data point (0,0)) is used to plot

$$Y = \frac{f-Kw}{Kw} \text{ and } X = \frac{1}{F}.$$

The capillary suction head is calculated by

$$Hc = \frac{C}{(ds)(n)}.$$

The first approach which involves 2 coefficients, a and b, appears to be a better way to fit the data, when possible, than the second approach which involves only one coefficient, C. The second approach will be employed only in cases were the first approach produces a value for a that is less than zero.

Another approach to the parameter estimation will involve the use of rainfall and runoff data from rainfall simulation on soil surfaces that are considered dry, wet, and very wet. The saturated hydraulic conductivity will be estimated from the runoff hydrograph of the very wet run. This run will be used because the term for capillary suction head times available porosity becomes very small as the soil approaches saturation and the infiltration rate more closely approximates saturated hydraulic conductivity at this time. Stone et al. (1987) estimate this value as Ks equals the final infiltration rate for the very wet run. A method of averaging runoff rates for the last portion of the application period, similar to that described above for Ward's second graphical approach, will be used to estimate the final infiltration rate. The saturated hydraulic conductivity parameter estimated from the very wet run will be used with the data from the dry run to estimate an effective potential term (Ns). This term incorporates initial soil moisture, total porosity, effective porosity and the capillary suction head. Using the IRS program of the WEPP model, Ns will be adjusted so that the calculated rainfall excess volume equals the observed runoff volume. Using soil moisture data, porosity determined from bulk density measurements and effective porosity, we will solve for the capillary suction head. Lane (personal communication) stated that the effective porosity, which is the total porosity adjusted for coarse fragments and entrapped air, generally is 90 to 95 percent of the total porosity. Rawls (personal

communication) feels that entrapped air may not be a significant factor when dealing with a forest road surface. An additional literature search will be conducted to attempt to define the relationships between entrapped air and coarse fragments and the infiltration process for forest roads.

The wet run will be used to verify the saturated hydraulic conductivity and capillary suction head estimated in the previous steps. This will be accomplished by comparing the rainfall excess values calculated by the IRS program with the observed runoff volumes.

The various parameter estimation techniques will be applied to determine which one is best suited for use in developing values for use on forest road surfaces. This determination will be based upon goodness-of-fit tests. Due to the relatively small sample size for each soil/geologic material, all of the relevant data will be used in estimating each parameter (Daniel and Wood 1971). Relevant data will be obtained from the uncovered 1 M^2 subplots. Screened 1 M^2 subplot data will be used only if it is apparent that no crusting is occurring during the rainfall application period. Traditional statistical procedure calls for withholding a randomly selected subset of the available data during model development and using this for model evaluation. This practice is of limited usefulness (Hamilton 1988) and will not be used in this study. To test how well the model describes the relationships of interest, data from the 1 M x 5 M subplots will be used. Previous work by the Engineering Technology Research Work Unit on forest roads in granitic and belt material may also be used in testing.

The values for saturated hydraulic conductivity and capillary suction head for each soil/geologic material will be related to measured site characteristics by means of regression equations. Independent variables to be initially included in the regression analysis will be bulk density, particle size

distribution information, organic matter content and slope. The relationship between the parameter values of interest and each of the variables will initially be analyzed graphically. Once a workable form of the equation has been developed, dummy variables will be used to identify if rainfall intensity and replicate plots at a site have effects on the relationships.

Summary

The study is being conducted to develop values for infiltration parameters to be used in the application of the WEPP model to forest roads and to relate these values to site characteristics for 4 types of soil/geologic material in the Northern Rocky Mountains. These relationships will be used to develop prediction equations so that forest managers can effectively use the WEPP model for forest roads. The success of the study will be measured by how well the WEPP model, using the derived parameter values, can reproduce runoff hydrographs produced by rainfall simulation.

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